RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 50, NUMBER 10 1 SEPTEMBER 1994-II

Origin of dissipation in high-T_c superconductors

Kazuo Kadowaki and S. L. Yuan*
National Research Institute for Metals, Tsukuba Laboratory, 1-2-1, Sengen, Tsukuba, Ibaraki 305, Japan

K. Kishio, T. Kimura, and K. Kitazawa
Department of Industrial Chemistry, University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113, Japan
(Received 3 June 1994)

Based on a systematic experimental study of the resistivity of high-quality single crystals of $(La_{1-x}Sr_x)_2CuO_4$, a phenomenological approach is proposed in which the dissipation for the direction perpendicular to the superconducting layers is explained by thermal fluctuations of the phase in Josephson junctions. By introducing an effective junction area $A(H,T)$, an analytical expression for the resistivity is formulated, with which the c-axis resistivity as a function of T, H, and θ (angle between H and the basal plane) can be very well explained.

Among many interesting experimental findings of high-T_c superconductors, the pronounced broadening of the resistive transition in a magnetic field is unique.[1] This discovery has initiated a serious question concerning the fundamental mechanism of dissipation in the vortex state, which has long been believed to be due to the motion of vortex lines in a superconductor.[2] Although many models have been proposed to explain this problem so far,[2,3] most of them were based on the traditional idea of vortex motion. These models, however, seem to work well only when part of the experimental results are taken into consideration. In order to overcome the problem in a conventional context, several approaches based on ideas such as vortex-antivortex excitations,[4] Josephson coupling,[5,6] giant fluctuations,[7] etc. have also been proposed. Nevertheless, it appears that none of them is satisfactory. In order to understand this problem better, we proposed a model that is essentially based on an idea that superconducting fluctuations[8] are due to an extremely short coherence length (especially perpendicular to the superconducting layers) and a large anisotropy in the superconducting order parameter. By extending this model we show that all features observed by experiments can be well understood even for the case where the Lorentz force is not active ($H \| I \| c$).

Although this proposal is essentially based on superconducting fluctuations, we take a classical idea in the Josephson-coupling model as a physical analogy. A similar approach has been proposed by Tinkham[9] and accounts for the phase slippage in the Josephson junction as an origin of dissipation. In his model, however, the origin of phase slippage was induced by flux creep, which is not relevant for the dissipation mechanism in our model. It also fails to explain the low-resistivity region where $\rho < 0.1\rho_n$ (Ref. 2) and the c-axis-resistivity broadening in magnetic fields parallel to the c axis.

The purpose of this paper is to propose a more appropriate description that can explain the c-axis resistivity very well, even where there is no Lorentz force exerted on the vortex lines. In addition, this approach can explain the resistivity over more than six orders of magnitude by taking the irreversibility line into account in the theory. This fact is simply deduced as a consequence of our analysis and may be an indication that the vortex state melts at the irreversibility line, above which there is no true superconducting order. Accordingly, the dissipation in this region is essentially caused by the phase slippage in effective Josephson junctions that located between adjacent superconducting layers because of strong superconducting fluctuations.

We have investigated the resistivity of well-characterized $(La_{1-x}Sr_x)_2CuO_4$ ($x = 0.068$) high-T_c single crystals in magnetic fields. The shape of these crystals are rectangular: the dimensions are $3.0 \times 2.18 \times 0.17$ mm^3, with the longest edge along the c axis for $I \| c$, and $4.5 \times 2.2 \times 0.32$ mm^3, with the shortest edge along the c axis for $I \| ab$. The resistivity was measured by either ac or dc four-probe methods with a current density of about 0.3 A/cm^2. The resistive transitions in magnetic fields were examined in four major configurations with respect to magnetic fields and current directions and crystallographic axes: ($H \| c \| I$), ($H \| c$, $I \| ab$), ($H \| ab$, $I \| c$), and ($H \| ab \| I$). Moreover, the angular dependence is also studied for the two cases: $I \| c$ and $I \| ab$ with H rotated from the c axis to the ab plane. The experimental results related to the problem are summarized as follows.

(i) The resistive transition becomes broadened significantly in such a way that the transition width is only governed by the field direction with respect to the crystallographic axis. This fact is generally confirmed in many high-T_c superconductors such as $(La_{1-x}Sr_x)_2CuO_4$ ($x = 0.075$),[7] $YBa_2Cu_3O_7$,[10] and $Bi_2Sr_2CaCu_2O_{8+\delta}$.[11] The normalized c-axis resistivity broadening phenomenon as an example is shown in Fig. 1 in the case of $(La_{1-x}Sr_x)_2CuO_4$ ($x = 0.068$) in various magnetic fields parallel to the c axis. (ii) The broadening is much wider for the field being parallel to the c axis than to the ab plane, irrespective of the current direction, indicating that the large anisotropic magnetic field effects are involved in this phenomenon. (iii) The c-axis resistivity in a magnetic field below the zero field transition temperature, T_{c0}, tends to increase further as temperature is decreased, following the one above T_{c0}, then falls off through a maximum value. (iv) The angular dependence of the resistivity with respect to the field orientation gradually sets in with lowering temperature without showing any sharp features in the vicinity of the mean field transition tempera-

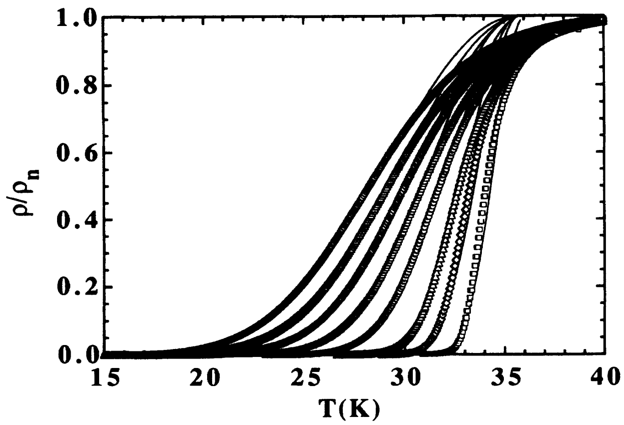

FIG. 1. The temperature dependence of the normalized c-axis resistivity in magnetic fields parallel to the c axis. The symbols from left to right (○), (△), (◇), (□), (○), (△), (◇), and (□) represent the experimental data points obtained in magnetic fields 6, 5, 4, 3, 2, 1, 0.5, and 0.1 T, respectively. The solid lines show the corresponding results calculated by the model proposed in this paper. The c-axis normal state resistivity follows $\rho_n(T) = 0.026\ \exp(51.746/T) + 0.148\,45(\Omega\ \mathrm{cm})$, which was extended to lower temperatures by fitting the resistivity data between 50 and 130 K.

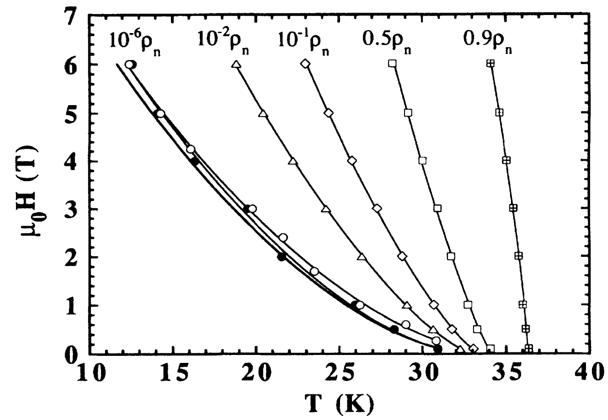

FIG. 3. The field dependence of the transition temperature T_c determined by the ρ-T data in $H \| I \| c$ in various different resistive criterions. The data points (open circles) determined by the lowest resistivity criterion of $10^6 \rho_n$, which is, in fact, the lower limit of the detectable resistivity in the present measurements, are located very close at the irreversibility line determined by the dc magnetization measurements (filled circles connected by a thin solid line). The bold and solid line represents the irreversibility line obtained from the present analysis as a fitting parameter. The field dependence of $T_{\mathrm{irr}}(H)$ is explained in the text.

ture in a magnetic field, $T_c(H)$, as the field is rotated from the c axis to the ab plane. An example of the angular dependence at 30 K is shown in Fig. 2. (v) The onset of the c-axis resistivity in fields parallel to the c axis agrees with the irreversibility line.

The first and the second points given above are the most important experimental facts needed to formulate the present model and have been interpreted differently within the framework based on the flux motion due to the Lorentz force, for instance, as proposed by Kes *et al.*,[12] who only took into account the large superconducting anisotropy. Although their model seems to explain essential features such as the angular dependence of the resistivity, the observed broadening of the c-axis resistivity in a magnetic field parallel to the c axis cannot be explained. This is the main reason for us to discard the conventional approach and naturally leads to a conclusion that the dominant mechanism for the resistivity broadening is caused by dissipation due to the non-Lorentz force driven mechanism. The third point given above strongly indicates that the conduction mechanism for the c axis is nonmetallic, but semiconducting or insulating. This additional evidence may also support our Josephson-coupling model between superconducting layers. The phenomena given in the fourth and fifth points suggest that there is no clear superconducting phase transition in magnetic fields near $T_c(H)$. The fact that the gradual development of such an angular dependence beginning from well above T_{c0} continues into low temperatures, especially in the systems with larger anisotropy and shorter coherence length in the superconducting state,[11] supports strongly evidence of superconducting fluctuations involved in this problem. In the following, we mainly focus our attention on the case where the Lorentz force is not active ($H \| I \| c$), since it is the most important case for the present model.

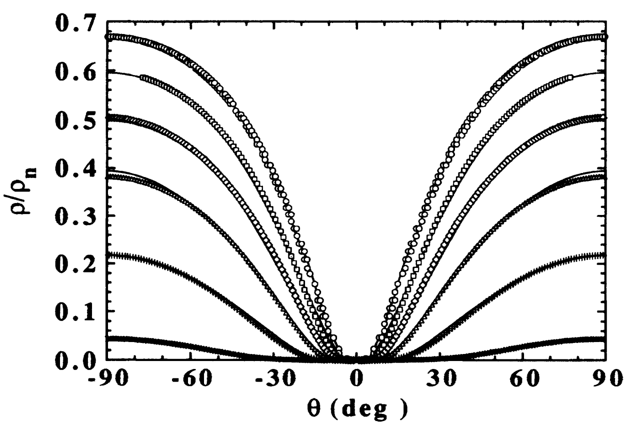

FIG. 2. The angular dependence of the normalized c-axis resistivity in magnetic fields: 6 (○), 5 (□), 4 (◇), 3 (△), 2 (+), and 1 T (×) from top to bottom at 30 K. The symbols represent the experimental data points. The calculated results in terms of the model proposed in this paper are also presented by the solid lines.

To begin we explore the role of the irreversibility line by plotting the c-axis-resistivity values in various magnetic fields with different resistive criterions in the H-T plane. As shown in Fig. 3, the onset of the resistivity is definitive as a converging value at a certain temperature in a given field. Moreover, it is important to note that the onset of the c-axis resistivity for the $H \| c$ axis coincides very well with the irreversibility line determined by magnetization measurements. This agreement together with the lack of a clear superconducting transition near $T_c(H)$ suggests that the true superconducting state with zero resistance may be realized below the irreversibility line only.

In order to give a consistent description on these findings, here we propose a phenomenological approach on the dissipation mechanism. We first introduce a conventional two-dimensional (2D) pancake picture, in which a flux line may be visualized as a stack of pancake vortices located at the different superconducting layers. These pancakes are coupled by the weak Josephson coupling. At higher temperatures above the irreversibility temperature, a straight stack of pancakes along the c axis is perturbed by the thermal effect, leading to dissociation of pancakes. According to Ambegaokar and Halperin's work,[13] the c-axis resistivity in such a case can be expressed as

$$\rho/\rho_n=\{I_0[E_j/2k_B(T-T_{\rm irr})]\}^{-2}, \tag{1}$$

where I_0 is the modified Bessel function and E_j is the Josephson-coupling energy. It is noted here that we replaced the thermal contribution k_BT in the conventional model[13] to $k_B(T-T_{\rm irr})$, since the true zero resistivity is achieved at the irreversibility temperature and below it as described above.

Following the Lawrence-Doniach model on the anisotropic 3D superconductors, the maximum Josephson supercurrent density J_0 perpendicular to the layers can be expressed as $J_0=\phi_0/2\pi\mu_0 s\lambda_c^2$,[14] where s is the interlayer spacing, ϕ_0 the flux quantum ($=h/2e$), and λ_c the penetration depth. By introducing an effective junction area $A(H,T)$, we obtain the maximum Josephson supercurrent flowing to the c direction as $I_{j\,\max}=A(H,T)J_0=A(H,T)\phi_0/2\pi\mu_0 s\lambda_c^2$. Therefore, the corresponding Josephson-coupling energy is expressed as

$$E_j=I_{j\,\max}\hbar/e$$
$$=A(H,T)\phi_0^2/2\pi^2\mu_0 s\lambda_c^2. \tag{2}$$

The effect of the magnetic field could be understood as follows. Applying the magnetic field perpendicular to the superconducting layers, a straight stack of pancakes is formed. This straight stack is disrupted by moving a pancake, resulting in a formation of Josephson strings between the superconducting layers. As a result, the phase change associated with the Josephson current between the adjacent junction layers is created within an effective junction area, $A(T,H)$. This effective junction area can be approximately proportional to $r_s\Delta r$, where $r_s(=s\gamma)$ is Josephson penetration depth which characterizes the range of the Josephson interaction, γ is the anisotropy ratio, and Δr is the relative displacement between the pancakes in the adjacent layers induced by positional thermal fluctuations. Therefore, one expects that the effective junction area should be proportional to $k_B(T-T_{\rm irr})$. Based on this argument, we write approximately the effective junction area as $A(H,T)=a(H)(\Delta T/T_c)^\alpha$, where $a(H)$ is only related to H and is decreased with increasing H, and $\Delta T=T-T_{\rm irr}$. The parameter α is introduced in order to absorb the effect of deviation from the exact linear temperature dependence of Δr, which in fact reflects the extent of the Josephson coupling between the layers, which will be described separately in detail.[15]

Inserting $A(H,T)$ into (2), we obtain the Josephson-coupling energy E_j as

$$E_j=[a(H)\phi_0^2/2\pi^2\mu_0 s\lambda_c^2](\Delta T/T_c)^\alpha. \tag{3}$$

Consequently, by putting (3) into (1), we obtain the expression of the c-axis resistivity for $H\|c$ as

$$\rho/\rho_n=\{I_0[a(H)\phi_0^2(\Delta T/T_c)^{\alpha-1}/4\pi^2\mu_0 s\lambda_c^2k_BT_c]\}^{-2}. \tag{4}$$

By assuming $\lambda_c(T)=\lambda_c(0)(1-T/T_c)^{-1/2}$, Eq. (4) can be rewritten as

$$\rho/\rho_n=\{I_0[C(H)(1-T/T_c)/(\Delta T/T_c)^{1-\alpha}]\}^{-2}, \tag{5}$$

where $C(H)=a(H)\phi_0^2/4\pi^2\mu_0 sk_BT_c\lambda_c^2(0)$, which only depends upon the field. This is the central result of this paper.

It is important to note that for conventional weak-coupled Josephson junctions with small anisotropy, Eq. (5) is naturally reduced to the AH model by putting $\alpha=0$ and $T_{\rm irr}=0$. This is confirmed in Nb/Nb films in H perpendicular to the junction.[16] For the case with a moderate anisotropy such as $YBa_2Cu_3O_{7-\delta}$ ($\gamma\approx8$), the Josephson coupling between the layers is rather strong, resulting in the behavior similar, to some extent, to that predicted by the AH model except for replacing T with $T-T_{\rm irr}$ in the expression of thermal energy. Therefore, the α value is expected to be close to zero. In contrast with this, for more anisotropic superconductors such as the $Bi_2Sr_2CaCu_2O_{8+\delta}$ system ($\gamma\geq200$), the Josephson coupling is so weak that the stack of 2D pancakes is easily broken up by thermal activation. Thus the α value is expected to be close to unity. From these arguments, it seems empirically that the parameter α is a pure material constant.

It is noted that there are four important parameters in Eq. (5). Among them, two parameters, $T_{\rm irr}$ and T_c, can be determined by experiments. The former is obtained on the basis of either dc magnetization data or resistivity data by the lowest limit of the resistivity criterion, which is given by the following formula: $T_{\rm irr}=33.2[1-(\mu_0H/12.85)^{0.57}]$ (μ_0H in tesla). Temperatures defined by $0.9\rho_n$ are used as T_c values in various magnetic fields. Therefore, the parameters left to be set are α and $C(H)$. By fitting the resistivity obtained at a fixed field, it turns out that the parameter α is close to 2/3, a constant value. Then, only one quantity $C(H)$ is used as a

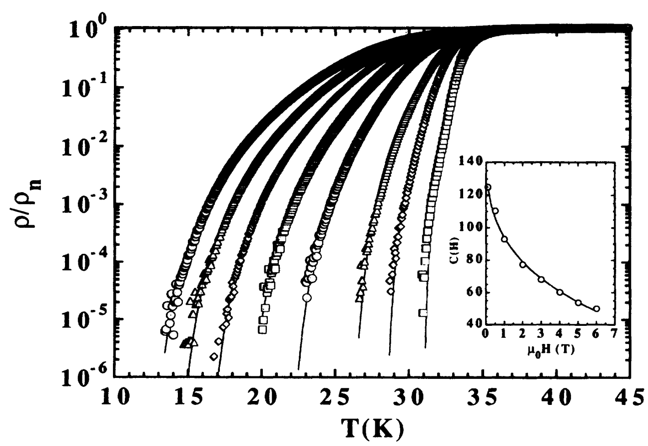

FIG. 4. Logarithmic plots of the c-axis-resistivity data shown in Fig. 1 together with the calculated results (shown by the solid lines) in magnetic fields parallel to the c axis. The symbols from left to right (○), (△), (◇), (□), (○), (◇), and (□) represent the experimental data points obtained in magnetic fields 6, 5, 4, 3, 2, 1, 0.5, and 0.1 T, respectively. Inset: the field dependence of the parameter $C(H)$ used in the present analysis. The curve for $C(H)$ is expressed well by $C(H)=8.57-2.22\ \ln(\mu_0H)$ (μ_0H in tesla).

fitting parameter. The experimental c-axis-resistivity data shown in Fig. 1 are replotted by the logarithmic scale together with the calculated results (presented by the solid lines) as shown in Fig. 4. The calculated resistivity plotted in the linear scale is also added in Fig. 1 (shown by the solid lines). The free parameter $C(H)$ determined by fitting is also plotted in the inset of Fig. 4 and can be well approximated by the following formula: $C(H)=8.57-2.22\ \ln(\mu_0 H)$ ($\mu_0 H$ in tesla). It is important to note that this expression for $C(H)$ is a very good approximation at high fields ($\mu_0 H > 2$ T). It can be seen that the calculated resistivities (solid lines) on the basis of the above model yield excellent agreement with the data except for the resistivity region $\rho > 0.9\rho_n$. Although we have tried to improve the fitting by adjusting the parameter $T_c(H)$ as a function of H, the obtained results often became unphysical in the sense that the field dependence of $T_c(H)$ is positive. As a consequence, T_c is fixed to be 36.1 K. We believe that this is caused mainly by two reasons. First, in the vicinity of $T_c(H)$ there must be strong critical fluctuations, which may induce effects beyond our Josephson-coupling model. Second, Eq. (5) is no longer appropriate as T close to T_c, since the measuring current becomes relatively important compared with the critical current.

Although Eq. (5) is obtained for the $H \| c$ axis, it is also appropriate for the magnetic field in an arbitrary angle θ with respect to the basal plane only by replacing H with the effective perpendicular component, $h=H(\sin^2\theta+\gamma^{-2}\cos^2\theta)^{1/2}$ in the field dependent quantities such as $a(H)$, $T_c(H)$, and $T_{\text{irr}}(H)$, where γ is the anisotropy ratio. Using this extended form, it is possible to calculate the c-axis resistivity as a function of H and θ at a fixed temperature.[15] As an example, the calculated results of the angular dependence of the resistivity in various fields on this basis are also included in Fig. 2 by the solid lines. The agreement between the experimental results and the calculated values is excellent and remarkable. It is worthwhile pointing out that the expression of the resistivity and all parameters used in this calculation are the same as those used in the ρ-T fitting except for replacing H with the effective field h.

In summary, we proposed a phenomenological approach to the c-axis-resistivity broadening in magnetic fields taking into account the phase slippage in the effective Josephson junctions. We obtained an analytical expression of the c-axis resistivity in the zero bias current limit as a function of temperature T, magnetic field H, and angle θ between H and the ab plane. The validity of this approach is simply manifested by the excellent agreements between the calculated and experimental results for a $(La_{1-x}Sr_x)_2CuO_4$ ($x=0.068$) high-quality single crystal.

---

*On leave from Institute of Plasma Physics, Academia Sinica, Hefei, China.

[1] For example, K. Kitazawa *et al.*, Jpn. J. Appl. Phys. **28**, L555 (1989); Y. Iye *et al.*, *ibid.* **26**, L1057 (1987); T. T. M. Palstra *et al.*, Phys. Rev. Lett. **61**, 1162 (1988).

[2] T. T. M. Palstra *et al.*, Phys. Rev. B **41**, 6621 (1990); R. Griessen, Phys. Rev. Lett. **64**, 1674 (1990); A. P. Malozemoff *et al.*, in *Strong Correlation and Superconductivity*, edited by H. Fukuyama, S. Maekawa, and A. P. Malozemoff (Springer-Verlag, Berlin, 1989), p. 349.

[3] P. H. Kes *et al.*, Supercond. Sci. Technol. **1**, 242 (1989).

[4] S. Martin *et al.*, Phys. Rev. Lett. **62**, 677 (1989); Y. Ando *et al.*, *ibid.* **67**, 2737 (1991).

[5] K. Kadowaki, in *Electronic Properties and Mechanisms of High-T_c Superconductors*, edited by T. Oguchi, K. Kadowaki, and T. Sasaki (North-Holland, Amsterdam, 1992), p. 373.

[6] G. Briceno *et al.*, Phys. Rev. Lett. **66**, 2164 (1991); D. H. Kim *et al.*, Phys. Rev. B **42**, 6249 (1990).

[7] K. Kitazawa *et al.*, in *Strong Correlation and Superconductivity* (Ref. 2), p. 361.

[8] T. Tsuneto, J. Phys. Soc. Jpn. **57**, 3499 (1988); R. Ikeda *et al.*, *ibid.* **60**, 1051 (1991).

[9] M. Tinkham, Phys. Rev. Lett. **61**, 1658 (1988).

[10] K. Kadowaki, J. N. Li, and J. J. M. Franse, Physica C **170**, 298 (1990).

[11] K. Kadowaki, in *Electronic Properties and Mechanisms of High-T_c Superconductors* (Ref. 5), p. 209.

[12] P. H. Kes *et al.*, Phys. Rev. Lett. **64**, 1063 (1990).

[13] V. Ambegaokar and B. I. Halperin, Phys. Rev. Lett. **22**, 1364 (1969).

[14] J. R. Clem, Phys. Rev. B **43**, 7837 (1991).

[15] S. L. Yuan *et al.* (unpublished).

[16] D. H. Kim *et al.*, Phys. Rev. B **45**, 7563 (1992).